MAGNETOMETER CALIBRATION SERVICES

Presenter

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Abstract--A new facility to calibrate magnetometers in San Diego has recently been completed as a cooperative effort between the Naval Primary Standards Laboratory and the National Institute of Standards and Technology. All measurements are NIST traceable through a nuclear magnetic resonance-based measurement. Magnetic fields from the 0.1 μT to 1.4 T can be calibrated by comparisons with fields generated by a series of coils or an electromagnet.

A new system to calibrate magnetometers has been installed at the Navy Primary Standards Laboratory (NPSL) in San Diego CA. The National Institute of Standards and Technology (NIST) does not offer a calibration service for magnetometers, but to ensure that the country's need in this area can be met the two laboratories have worked together to provide a system at NPSL in which magnetic calibrations can be traced to NIST through nuclear magnetic resonance (NMR) measurements.

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The NMR connection-- An experiment conducted at NIST (reported in 1989(1)) measured a conversion factor which relates a magnetic field measurement based on current and dimensions with one measured in terms of frequency, via NMR. This conversion factor, called the gyromagnetic ratio of the proton, is a constant of nature. The proton has a magnetic moment, μ_p, and an angular momentum, 1/2 $\hbar$, where $\hbar = h/2\pi$ and h is Plank's constant; therefore, in a magnetic flux density, B, protons absorb a quantum of energy in changing from parallel to antiparallel alignment to the magnetic flux. The frequency, ν, of this energy is given by the simple equation,

$$\Delta E = h\nu = 2\mu_p B \qquad \text{or} \qquad \omega_p = 2\pi\nu = (2\mu_p/\hbar)B\,.$$

The quantity $2\mu_p/\hbar$ is given the symbol γ_p and called the gyromagnetic ratio of the proton. The frequency ω_p can be measured by NMR techniques. For protons in a spherical sample of water at a temperature of 25°C, the symbol is given a prime, γ_p'. The current best value for γ_p' is(1),

$$\gamma_p' = 2.67515427(28)\ 10^8\ T^{-1}\ s^{-1}$$

where the current used to produce the field B was measured in terms of the SI-90 definition for the volt and ohm.

Using this conversion factor, one can determine magnetic fields accurately by measuring a frequency via NMR in water, or measuring some other frequency for which the ratio of nuclear or electron moment to protons in water is known. However, these NMR devices usually require a uniform field to function well. Other magnetometers, such as a Hall effect probe or a fluxgate, are easy to use but need regular calibration.

Calibration coils and ranges-- At NPSL, magnetic fields from 0.1 μT to 1.4 T can be generated with a series of three coils and an electromagnet. A three-axis set of Helmholtz coils which can generate fields from 0 mT to 0.1 mT is used for low accuracy measurements, i.e., standard uncertainty of 0.05%. A precision glass solenoid can produce 0 mT to 1.2 mT with a standard uncertainty of 0.002%, and it fits inside the Helmholtz coils. The Helmholtz coils can reduce the background (Earth's) field when using the glass solenoid. Another Helmholtz coil is used to produce fields from 1 mT to 10 mT with 0.1% standard uncertainty. An electromagnet can be used to produce fields in the 40 mT to 1.4 T range. A more detailed description of the key coil systems is described below. A drawing and photograph of the low field system are shown in Figs. 1 and 2.

Three-axis Helmholtz coils-- This commercially made coil system can be operated in two modes. In the first mode it is used to cancel out background fields so that the precision solenoid, when placed inside the Helmholtz coils, can be used without any additional fields adding to the accurate solenoid field. In this mode, three constant current sources are adjusted using a single-axis fluxgate magnetometer that can be physically reversed to correct for the zero offset in the fluxgate. Temporal variations in the background are not servoed out, but the solenoid field can be distinguished by reversing its current direction.

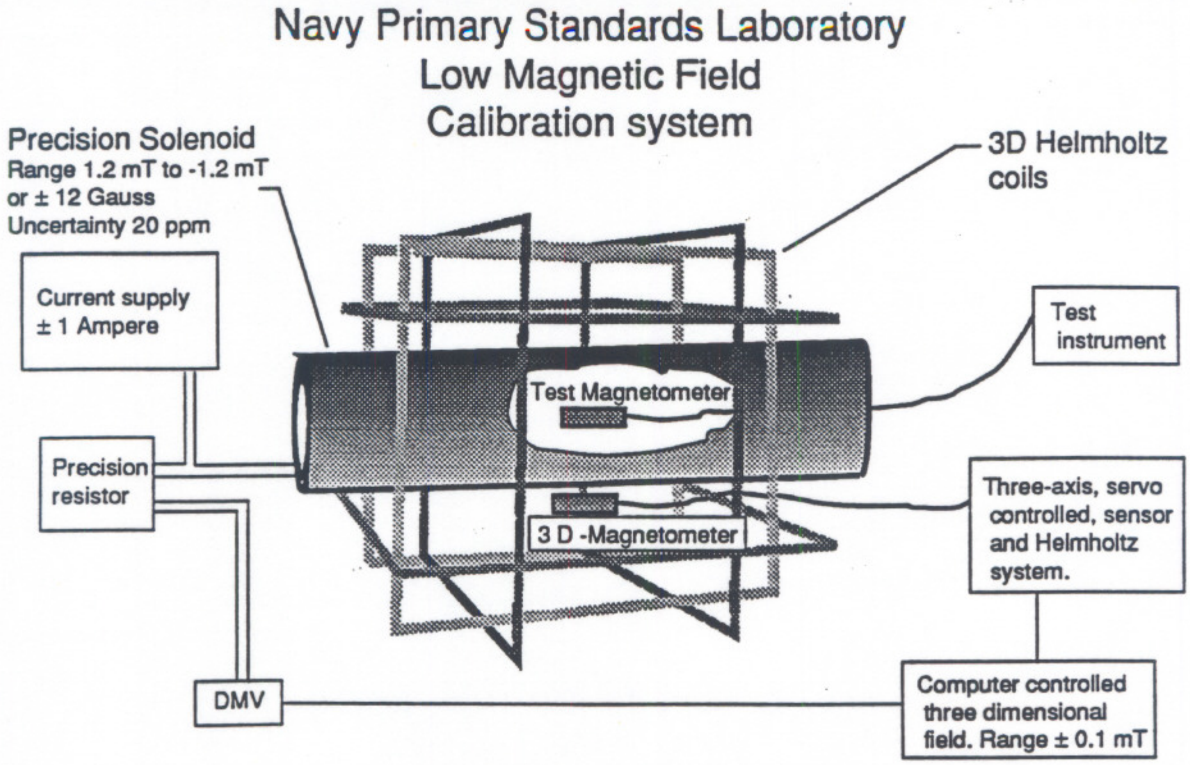

Figure 1. Low Magnetic Field Calibration System.

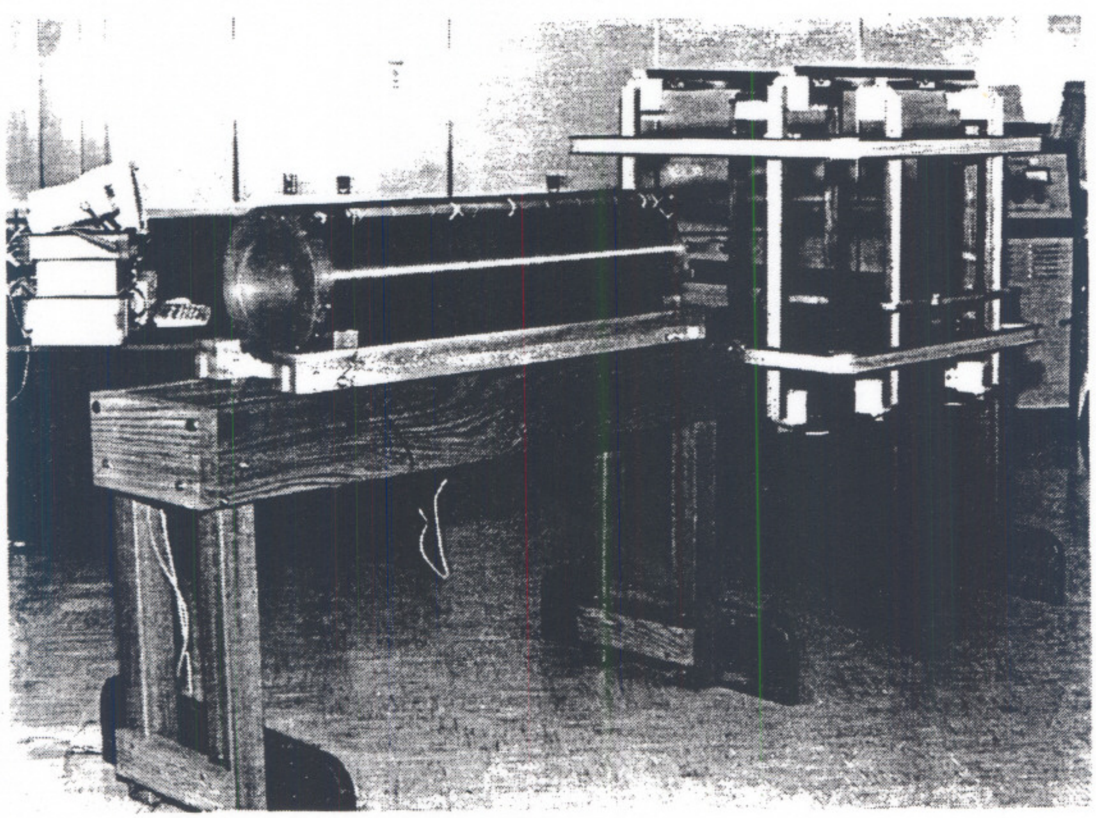

Figure 2. Photograph of Low Field System.

In the second mode, a three-axis fluxgate magnetometer is placed about 14.5 cm below the center of the three Helmholtz coils. The signals from each of the three magnetometers provide the inputs to a feedback system. This results in each Helmholtz coil receiving a feedback current so that its controlling magnetometer reads zero. Inside the three-axis fluxgate magnetometer, an offset field can be applied in each direction. When this magnetometer offset is changed, the field at the center of the Helmholtz coils changes proportionally. The single-axis fluxgate, which can be calibrated in the glass solenoid, is used to calibrate each axis of the Helmholtz system. Then, using the computer, one can apply any field in the range $\pm$ 0.1 mT with 16 bit resolution in each of the three directions. Because of the feedback arrangement the noise due to changes in the background field is significantly reduced. Only a gradient in the background field between the three-axis fluxgate magnetometer and the Helmholtz coil center is not servoed out. Therefore, magnetic noise sources that are far away are eliminated. This system is easy to use and has a standard uncertainty of 0.05% or less depending on how often it's calibrated against the glass solenoid.

The precision glass solenoid-- The unique feature of this low field calibration system is the glass solenoid. It has excellent long term dimensional stability and it produces a uniform field, such that a good NMR signal can be obtained at low fields. It is a single layer solenoid wound on a 6 cm thick glass cylinder (low thermal expansion) that has grooves ground and lapped with a 1.00008 mm/turn pitch. The wire was drawn through a die to make it round and of uniform diameter (0.7 mm). It has one thousand turns (1.00008 m long) and is 349 mm in diameter. Two 7-turn windings are wound as a second layer with insulated wire (0.8 mm) centered at $\pm$172 mm from the center. These extra 14 turns were added to provide compensating coils. These compensating coils were designed to operate with the same current as is in the primary solenoid; thus they are wired in series. The resulting field along the axis $(B(z)-B(0))/B(0) < 0.0002\%$ over $z = \pm 20$ mm and $< 0.02\%$ over $z = \pm 50$ mm. Using a pre-polarized flowing water NMR system(2) we measured the field-to-current ratio to be:

1.208118(24) mT/A with the solenoid glass temperature of 25° C.

In practice, the solenoid could be calibrated with at least another order of magnitude improved accuracy when needed. At present most instruments needing calibration, Hall-type Gauss meters and Fluxgate magnetometers, are vector sensing devices. The NMR calibration measures only the magnitude, for the protons precess about the field being measured. Therefore, the primary limiting uncertainty of most calibrations is caused by the alignment difficulties for the vector sensing devices. This uncertainty must be evaluated on a case by case basis.

Ten mT Helmholtz coil-- A smaller (30 cm mean diameter) many-turn Helmholtz coil can be used to calibrate fields from 2 mT to 10 mT, with a standard uncertainty of 0.1%.

Electromagnet-- A commercial electromagnet can be adjusted to field values between 40 mT and 1.4 T. A commercial NMR proton magnetometer and the instrument under test are inserted in the field and the NMR readings are used to calibrate the instrument. The field gradient between the two probes is very small. A correction for the gradient can be applied, but it is usually small enough to be neglected.

To calibrate standard magnets the electromagnet is adjusted to nominally the same field as the standard, and a Hall probe employed to transfer the NMR calibrated field value to the standard magnet.

Summary-- A service once offered by the Navy Eastern Standards Laboratory (Washington DC) has been improved and moved to NPSL, San Diego. Magnetic fields traceable to NIST are used to calibrate Hall effect meters, fluxgate magnetometers, flip coils, standard magnets and most other devices needing dc magnetic fields from 0.1 μT to 1.4 T.

(1) Williams, Edwin R, Jones, George R. Jr., Ye, Sheng, Liu, Ruimin, Sasaki, Hitoshi, Olsen, Paul T., Phillips, William D., and Layer, Howard P., "A low field determination of the proton gyromagnetic ratio in water," IEEE Trans. Instrum. Meas., vol. IM 38, April 1989, pp. 233-237.

(2) Kim, Cheol G., Williams, Edwin R., Sasaki, Hitoshi, Ye, Sheng, Olsen, Paul T., and Tew, Wes L., "Nuclear Magnetic resonance-based current-voltage source," IEEE Trans. Instrum. Meas., vol. IM 42, April 1993, pp. 153-156.